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PROBABILISTIC SEISMIC ASSESSMENT OF POUNDING FORCES

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ABSTRACT

Seismic pounding between adjacent structures might produce significant damage in many engineering systems. Thus, an accurate evaluation of the probability of occurrence of this event and the resulting consequences on the performance of a system is of paramount importance for seismic risk assessment purposes.
This study aims at providing a contribution towards the development of a methodology consistent with modern Performance-Based Earthquake Engineering approaches for the evaluation of the effects of pounding. In particular, the focus is on the estimation of the probabilistic distribution of the impact forces due to pounding.
A simplified benchmark model is considered, representing an isolated system surrounded by a moat wall, or a two-span bridge, and viscoelastic elements are defined to simulate the impact occurring during the earthquake. After nondimensionalizing the equations of motion, a parametric study is carried out to analyze the influence of each input parameter on the probabilistic distribution of the impact forces under the stochastic seismic input, and a simplified regression model is fitted. A simulation-based approach is then employed to obtain accurate estimates of the pounding force statistics and the results of these simulations are used to evaluate the accuracy of the simplifying approach for pounding force assessment based on the proposed probabilistic model.

Keywords: Pounding; Impact forces; Dimensional analysis; Probabilistic seismic demand model; Risk assessment.

1. INTRODUCTION

Events like earthquakes are likely to induce pounding between adjacent structures with different dynamic characteristics and insufficient separation distance. In particular, dynamic impacts represent a problem in densely built-up area, where adjacent structures can be in a full or partial contact with each other. Many cases related to structural damages due to impacts in neighboring buildings have been reported (Bertero and Collins 1973, Moehle and Mahin 1991, Penzien 1997). The same phenomena can affect different typologies of structural systems or structural elements (Masroor and Mosqueda 2012, Kim et al. 2015). For example, structural damages due to the pounding have been reported in several bridges in past seismic events, such as in the 1995 Kobe earthquake (Otsuka et al. 1996). Taflanidis (2011) has shown that pounding forces lead to high impact stresses in the bridge deck, the support bearings, and the substructures, and the non-uniform seismic excitation in long bridges exacerbates the problem. Pounding action may also result in areas of damage located around the corners of the deck or in large differential settlements on the abutments side with a consequent presence of cracks (Han et al. 2009). Dynamic impacts can occur even between base-isolated buildings and the surrounding moat walls (Darragh et al. 1994, Taflanidis and Jia 2011, Nagarajaiah et al. 2001), leading to a significant increase in the superstructure response. Impact phenomena can also represent an issue in the nuclear field. Pellissetti et al. (2017) have studied how plastic deformations, due to impacts between fuel assemblies in a nuclear reactor, can affect the reliability of a safety shutdown for increasing seismic intensity levels.

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While there is a significant number of works on the evaluation of the critical separation distance to avoid impact (Chase et al. 2014, Tubaldi et al. 2012, Barbato and Tubaldi 2013, Tubaldi et al. 2016, Lopez Garcia et al. 2009), there are fewer studies on the consequence of pounding, and the investigations carried out are often limited to the analysis of specific systems and for fixed excitation levels or gaps (Bi et al. 2010, Anagnostopoulos 1988, Pantelides and Ma 1998, DesRoches and Muthukumar 2002). Only a few analyses and researches have been aimed to achieve a more in-depth understanding of the parameters that govern the pounding problem (Dimitrakopoulos et al. 2009, Zhai et al. 2014). There are also limited studies on the characterization of the impact forces (Jankowski 2006, Yaghmaei-Sabegh and Jalali-Milani 2012, Vega et al. 2009). These studies however focus only on the mean response for a reduced set of records, disregarding the record-to-record variability effects on the response dispersion. Moreover, they do not consider the key role played by stiffness parameter of the pounding model (Van Mier et al. 1991, Guo et al. 2012), and its influence on the estimate of the pounding forces.
The aim of this work is to furnish a preliminary evaluation of the most important parameters that control the impact forces due to pounding. For this purpose, a simplified pounding system is considered, consisting of a single degree of freedom linear elastic system prone to pounding. Though simple, the proposed model can represent some real-life systems such as isolated buildings pounding against the moat walls and two-span bridges pounding against the abutments. A modified Kelvin–Voigt element is adopted (Komodromos et al. 2007) as impact model, whereas a stochastic model (Atkinson and Silva 2000) is employed to describe the uncertainty in the seismic input intensity and characteristics. Through a dimensional study, the non-dimensional parameters characteristic of the seismic input and of the system that controls the problem at hand are derived. A general probabilistic seismic demand model is then proposed, providing useful information on the effect of the separation gap, the seismic input intensity, the system properties, and the impact stiffness, on the pounding forces mean value and dispersion. In the final part of the paper, the proposed demand model is validated against the results of simulations by considering few examples corresponding to different combinations of the system properties. The Matlab toolbox OpenCossan (Patelli et al. 2016) is used for the validation stage.

2. DIMENSIONAL ANALYSIS

2.1 Impact model

The numerical analysis of an impact problem entails choosing an appropriate impact model capable to properly describe the collision phenomena. On this regard, an important number of contact force models have been studied and proposed so far (Flores et al. 2011, Banerjee 2017). In general, dissipative models lead to a more realistic characterization of the contact mechanism, due to the energy losses always present in the compression and expansion stage. The Kelvin-Voigt model, consisting of a stiff linear spring in parallel with a damping element, represents the first proposed dissipative model (Goldsmith 2001). This model has the drawback that it returns unrealistic tensile forces immediately before separation. Komodromos et al. (2007) improved this model by imposing that the impact force goes to zero when it changes sign after the initial impact. The introduced modification, compared to the classic linear viscoelastic model, allows avoiding tensile force developed during the restitution stage due to the presence of the damping term. Another commonly employed structural impact model uses a non-linear impact spring, based on Hertz's contact law (Jankowski 2005). This model is however not employed in this study because of the higher simplicity of the modified viscoelastic model and its convenience for application of the dimensional analysis method (Zhai et al. 2015).
According to the Komodromos et al. (2007) model, the evolution of the impact forces during the seismic action can be expressed as follows:

$$F_{imp} = k_{imp} \cdot \delta(t) + c_{imp} \cdot \dot{\delta}(t) \text{ when } F_{imp} > 0 \tag{1}$$

$$F_{imp} = 0 \text{ when } F_{imp} \leq 0 \tag{2}$$

where k_{imp} represents the impact stiffness, while $\delta(t)$ and $\dot{\delta}(t)$ are the interpenetration depth and the

relative velocity, respectively.
The impact damping coefficient c_{imp} is defined as follows:

$$c_{imp} = 2\xi_p m\sqrt{\frac{k_p}{m}} \text{ ; with } \xi_p = \frac{-\ln(\varepsilon_N)}{\sqrt{\pi^2 + (\ln(\varepsilon_N))^2}} \tag{3}$$

where ε_N is the coefficient of restitution characterizing the energy dissipation during impact.
The described impact element is added to a single-degree-of-freedom (SDOF) system (Figure 1) to simulate collisions between the superstructure and the lateral walls.

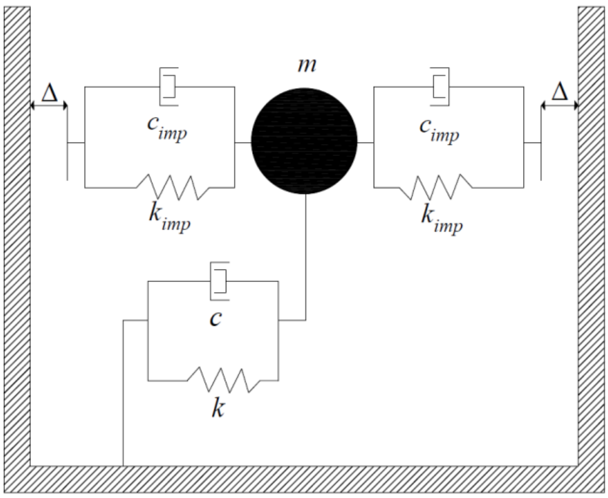


Figure 1. Pounding single-degree-of-freedom system analyzed.

2.2 Nondimensionalization of the equation of motion accounting for pounding

The equation of motion for a SDOF systems under seismic excitation undergoing pounding is:

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) + f_p(t) = -m \cdot \ddot{u}_g(t) \tag{4}$$

where

$$f_p(t) = f_p\left[\varepsilon_N, \Delta, x(t), \dot{x}(t)\right] \tag{5}$$

denotes the pounding force exchanged between the two systems, and Δ is the gap between the adjacent systems. The impact model for $f_p(t)$ is reported in Equations 1,2.
During impact with the right wall (the case of impact with the left wall can be treated in the same way):

$$\ddot{x}(t) + \frac{c}{m}\dot{x}(t) + \frac{k}{m}x(t) + \frac{k_{imp}(x(t)-\Delta) + c_{imp}\dot{x}(t)}{m} = -\ddot{u}_g(t) \tag{6}$$

This can be rewritten as:

$$\ddot{x}(t) + 2\xi\omega\dot{x}(t) + \omega^2 x(t) + \omega_p\left[\omega_p(x(t)-\Delta) + 2\xi_p\dot{x}(t)\right] = -a_0 l(t) \tag{7}$$

with

$$\omega_p = \sqrt{\frac{k_{imp}}{m}}; \omega = \frac{2\pi}{T} = \sqrt{\frac{k}{m}}; \xi_p = \frac{c_{imp}}{2m\omega_p} \tag{8}$$

where $l(t)$ is the ground motion history scaled by the acceleration intensity a_0.

After introducing the dimensionless time τ such that $\tau = t\omega$, one obtains:

$$\frac{\omega^2 \ddot{\bar{x}}}{a_0}(\tau) + \frac{2\xi\omega^2 \dot{\bar{x}}(\tau)}{a_0} + \frac{\omega^2 \bar{x}(\tau)}{a_0} + \frac{\omega_P\left[\omega_P\left(\bar{x}(\tau) - \Delta\right) + 2\omega\xi_p \dot{\bar{x}}(\tau)\right]}{a_0} = -\bar{\lambda}(\tau) \tag{9}$$

Introducing the dimensionless displacement $\psi(\tau)$, one finally obtains:

$$\ddot{\psi}(\tau) + 2\xi\dot{\psi}(\tau) + \psi(\tau) + \Pi_{\omega_p}^2\left[\psi(\tau) - \Pi_\Delta\right] + 2\xi_p\dot{\psi}(\tau)\Pi_{\omega_P} = -\bar{\lambda}(\tau) \tag{10}$$

with

$$\psi(\tau) = \frac{\omega^2 \bar{x}(\tau)}{a_0}; \Pi_{\omega_p} = \frac{\omega_p}{\omega} = \sqrt{\frac{k_{imp}}{k}}; \Pi_\Delta = \frac{\omega^2\Delta}{a_0} \tag{11}$$

In particular, Π_Δ is a dimensionless gap, already found by Vega et al. (2000).
The dimensionless pounding force depends also on the vibration period of the system through $\bar{\lambda}(\tau)$. In fact, by changing T, also the shape of $\bar{\lambda}(\tau)$ for a given record changes. This has been explained in other studies carrying out the non-dimensional analysis of similar systems (Tubaldi et al. 2015). Thus, Π_{fp} can be expressed as a function of the following parameters:

$$\Pi_{f_p} = \frac{f_p}{ma_0} = f\left(\Pi_{\omega_p}, \xi_p, \Pi_\Delta, \omega\right) \tag{12}$$

3. PARAMETRIC STUDY

3.1 Seismic input

The stochastic ground motion model proposed by Atkinson and Silva (2000) is employed to account for the uncertainty inherent to the seismic input. The ground motion's radiation spectrum $A(f;M,r)$ and its variability in the time domain $e(t;M,r)$, expressed as functions of the magnitude M and the epicentral distance r, define completely the model. In particular, the uncertainty connected to M and r is modeled by a truncated Gutenberg-Richter law and a triangular probability distribution function respectively.

$$A(f;M,r) = (2\pi f)^2 \cdot E(f;M) \cdot P(f;r) \cdot G(f) \tag{13}$$

$$e(t;M,r) = a_t\left(t/t_n\right)^{b_t} \cdot \exp(-c_t(t/t_n)) \tag{14}$$

$E(f;M)$ represents the source spectrum, $P(f;r)$ considers the path effects on the signal; $G(f)$ is the site response contribution, while in the Equation 14 the constants a_t, b_t and c_t are specific parameters chosen in relation to the peak value assumed by the envelope function. A step-by-step procedure for the definition of a single synthetic accelerogram in the time domain, by starting from the generation of a white noise, is described by Atkinson and Silva (2000), while additional details regarding the assumed probabilistic distributions of M and r can be found in Altieri et al. (2017).

The spectral acceleration $S_a(T,\xi)$ at the fundamental period T of the system and for a damping ratio ξ=5%, is assumed as intensity measure (IM) parameter, because it has been shown to be highly correlated with the pounding effects (Vega et al. 2009). This parameter is useful for the estimation of the risk of exceedance of the pounding force, as discussed in the next section. By assuming $S_a(T,\xi)$ as IM, $\Pi_\Delta=\omega^2\Delta/S_a(T,\xi)$ represents the ratio between the gap capacity and the gap demand, i.e., the spectral displacement of the system. It is more useful to consider its reciprocal $1/\Pi_\Delta$, such that the pounding force is zero for $1/\Pi_\Delta<1$.

3.2 Results

Having defined the dimensionless parameters that control the response of the pounding SDOF system, an extensive parametric analysis is carried out to evaluate their contribution to the normalized peak force Π_{fp}. For this purpose, a total of 25 records are sampled from the stochastic earthquake model, and for each combination of the system parameters, the median value of $\widehat{\Pi}_{fp}$ and the variance β are computed. An explicit Runge-Kutta method (Bogacki and Shampine 1989), with a time-step of 10^{-5} seconds, is employed to solve the second order differential equations. The values considered for $\Pi_{\omega p}$, $1/\Pi_\Delta$ and T are reported in Table 1. Figures 2 and 3 show respectively the median and dispersion of the nondimensional pounding force (respectively $\widehat{\Pi}_{fp}$ and β) vs T and $1/\Pi_\Delta$, for 5 different values of $\Pi_{\omega p}$.

Table 1. Input values for the parametric study

	Values								
$1/\Pi_\Delta$	1	1.1	1.2	1.3	1.4	1.5	2	5	10
Π_{ω_p}	5	10	50	100	500				
T [s]	0.1	0.5	1	2	4				

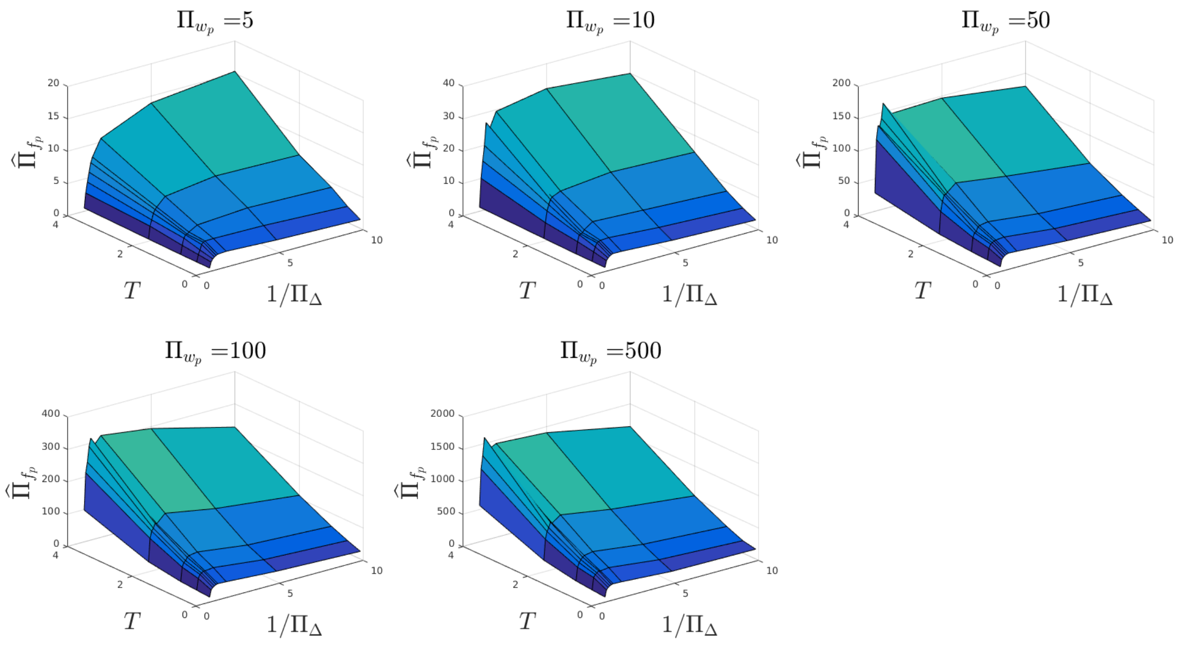


Figure 2. Median nondimensional pounding force vs T and $1/\Pi_\Delta$ for $\Pi_{\omega p}$ = [5,10,50,100,500]

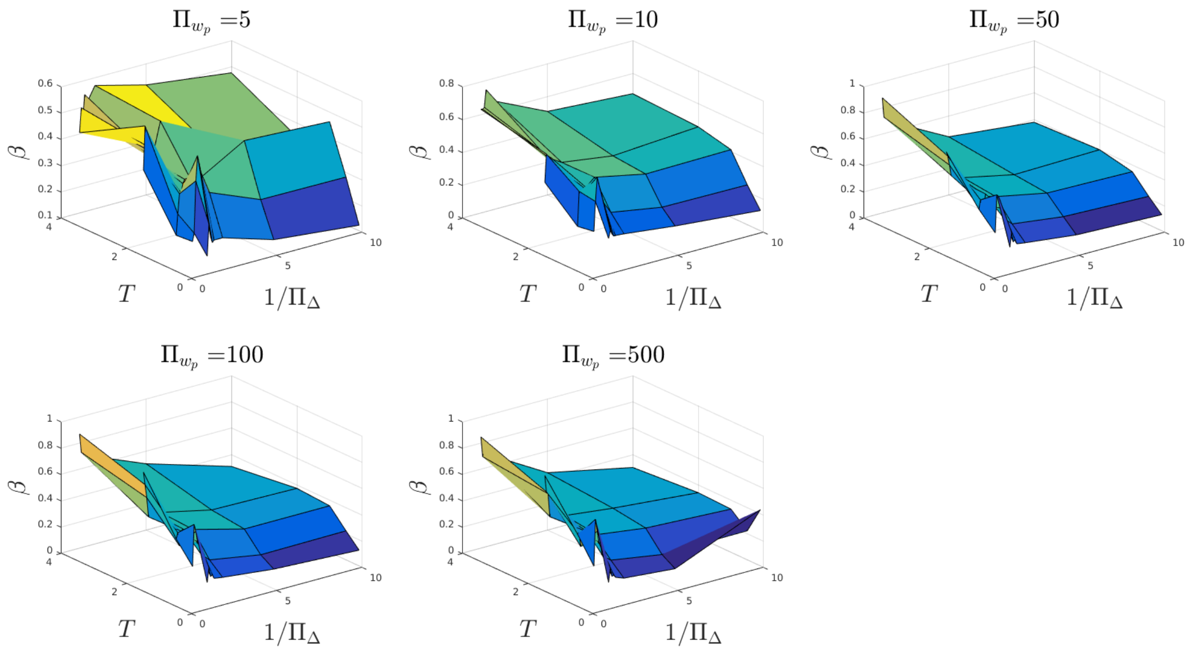


Figure 3. Dispersion of the nondimensional pounding force vs T and 1/ Π_Δ for $\Pi_{\omega p}$ = [5,10,50,100,500]

It is observed that for increasing values of 1/ Π_Δ (i.e., increasing seismic intensity or decreasing gap) the median normalized impact force increases more than linearly until it reaches an almost constant value which is different for each input parameter combination. On the other hand, $\widehat{\Pi}_{fp}$ increases almost linearly with the period and with the normalized impact stiffness $\Pi_{\omega p}$. The value of $\Pi_{\omega p}$ is shown to affect significantly the obtained values, thus confirming that the proper choice of this parameter is of paramount importance for an accurate estimation of the impact forces.

The beta parameter β, that accounts for the variance, shows almost a constant behavior except for decreasing values of 1/ Π_Δ, where a relevant variability is present, especially for smaller $\Pi_{\omega p}$.

4. PROBABILISTIC POUNDING DEMAND MODEL

4.1 Regression model

The results provided by the parametric study can be used as training set for the definition of a dimensionless demand model, assuming as input and output the vectors $\mathbf{\Gamma}$=[Π_Δ, $\Pi_{\omega p}$, T] and $\mathbf{\Phi}$=[$\widehat{\Pi}_{fp}$, β], respectively. The adopted regression model is given by the following equation:

$$\hat{\Pi}_{f_p}\left(\Pi_\Delta,\Pi_{wp},T\right)=I\cdot a\cdot\left(e^{-b\cdot\left(\frac{1}{\Pi_\Delta}-1\right)}-e^{-c\cdot\left(\frac{1}{\Pi_\Delta}-1\right)}\right)\cdot g(T)\cdot t(\Pi_{wp})\cdot\varepsilon \qquad (15)$$

where ε is the error due to the lack of fit, I represents an indicator function equal to 1 when impacts occur and 0 otherwise, $g(T)$ and $t(\Pi_{\omega p})$ are linear functions depending on T and $\Pi_{\omega p}$.

Similarly, a regression model is proposed to estimate β starting from $\mathbf{\Gamma}$:

$$\beta\left(\Pi_\Delta,\Pi_{wp},T\right)=h(\Pi_\Delta)\cdot w(T)\cdot q(\Pi_{wp})\cdot\varepsilon \qquad (16)$$

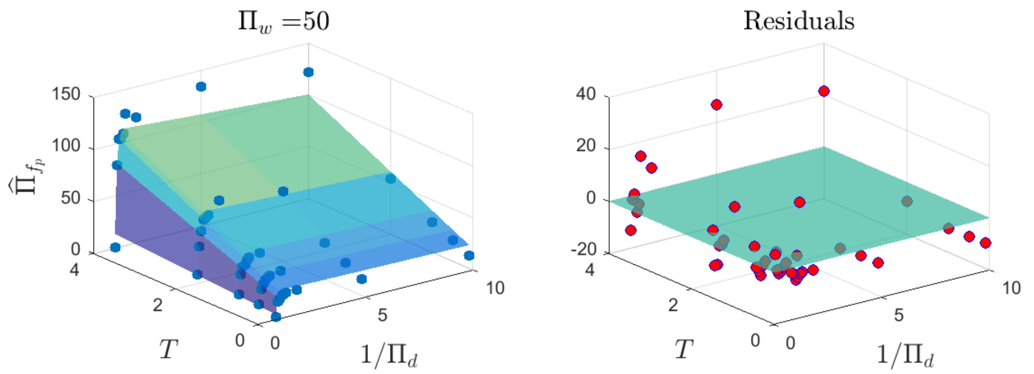
where β is expressed as a combination of three linear functions depending on Π_Δ, T, and $\Pi_{\omega p}$.

The constant terms in the Equations 15,16 are identified by minimizing the sum of squares of all the residuals through the Levenberg-Marquardt optimization algorithm (More 1978). The final parameters of both the regression models are reported in Table 2.

Table 2. Regression's parameters and R^2 values

	R^2	a	b	c	g_1	g_2	t_1	t_2
$\hat{\Pi}_{f_p}\left(\Pi_\Delta, \Pi_{wp}, T\right)$	0.978	16.944	0.014	12.495	1.220	1.211	-0.001	0.022
	R^2	h_1	h_2	w_1	w_2	q_1	q_2	
$\beta\left(\Pi_\Delta, \Pi_{wp}, T\right)$	0.671	-0.036	0.001	-17.480	-5.955	0.487	0	

(a)



(b)

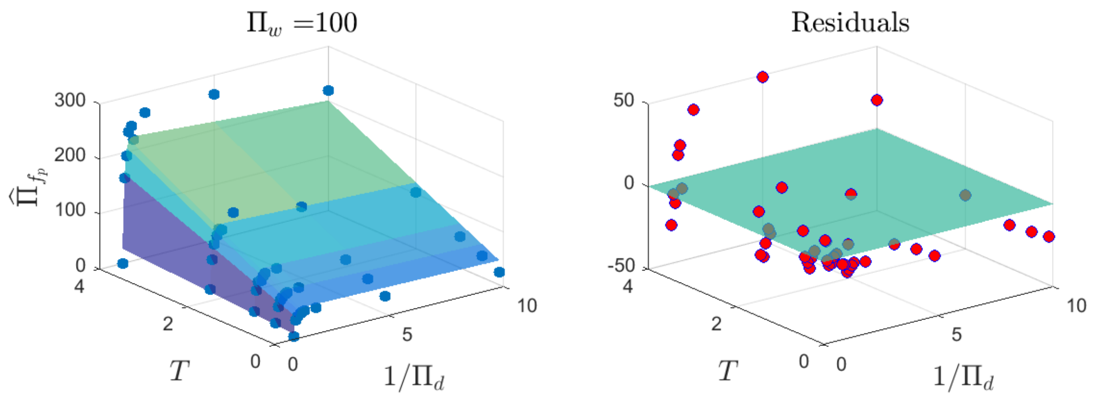


Figure 4. Comparison in terms of $\widehat{\Pi}_{fp}$ between the parametric study and the regression model for (a) $\Pi_{\omega p}$=50 and (b) $\Pi_{\omega p}$ =100

4.2 Comparison against numerical simulations

The proposed demand model defined by Equations 15,16 can be used in the context of a risk assessment framework such as the Performance-Based Earthquake Engineering (PBEE) framework (Cornell and Krawinkler 2000, Altieri et al. 2016), to evaluate the mean annual frequency of exceedance of the impact forces $v(F_p \geq f_p)$ of any structural configuration corresponding to the model of Figure 1. This can be expressed as $v(F_p \geq f_p)=v_0 P(F_p \geq f_p)$, where v_0 is the mean annual frequency of exceedance of any event of magnitude higher than m_{min}, and $P(F_p \geq f_p)$ is the probability of exceedance of the impact forces for any earthquake occurrence. First of all, a hazard curve $v(IM \geq im)$ is derived for the intensity measure $S_a(T,\xi)$. From this curve, it is possible to obtain the complementary cumulative distribution $G_{IM}(im) = P(IM \geq im) = v(IM \geq im)/v_0$.

The proposed demand model provides the median value $\hat{f}_p$ and the associated variance β of the impact forces at different seismic intensity levels, and the probability of exceedance $P(F_p \geq f_p \mid IM = im)$ conditional to $IM = im$ can be evaluated under the assumption of lognormality (Jalayer et al. 2007,

Pellissetti et al. 2017).
Finally, the unconditional probability of exceedance $P(F_p \geq f_p)$, can be estimated by solving numerically the following convolution integral:

$$P(F_p \geq f_p) = \int_{im} P(F_p \geq f_p \mid IM = im) \left| \frac{dG_{IM}(im)}{d(im)} \right| \tag{17}$$

The exceedance probability computed based on the proposed demand model can be compared with the one obtained via Latin Hypercube sampling (LHS) (McKay et al.1979), which does not require conditioning to the IM. Table 3 provides the input parameters selected for comparison purposes and the results are reported in Figure 5.

Table 3. Input values for the comparison with numerical simulation

T[s]	**Δ [m]**	***m* [ton]**	Π_{ω_p}
1	[0.005-0.01-0.02-0.03]	1000	50

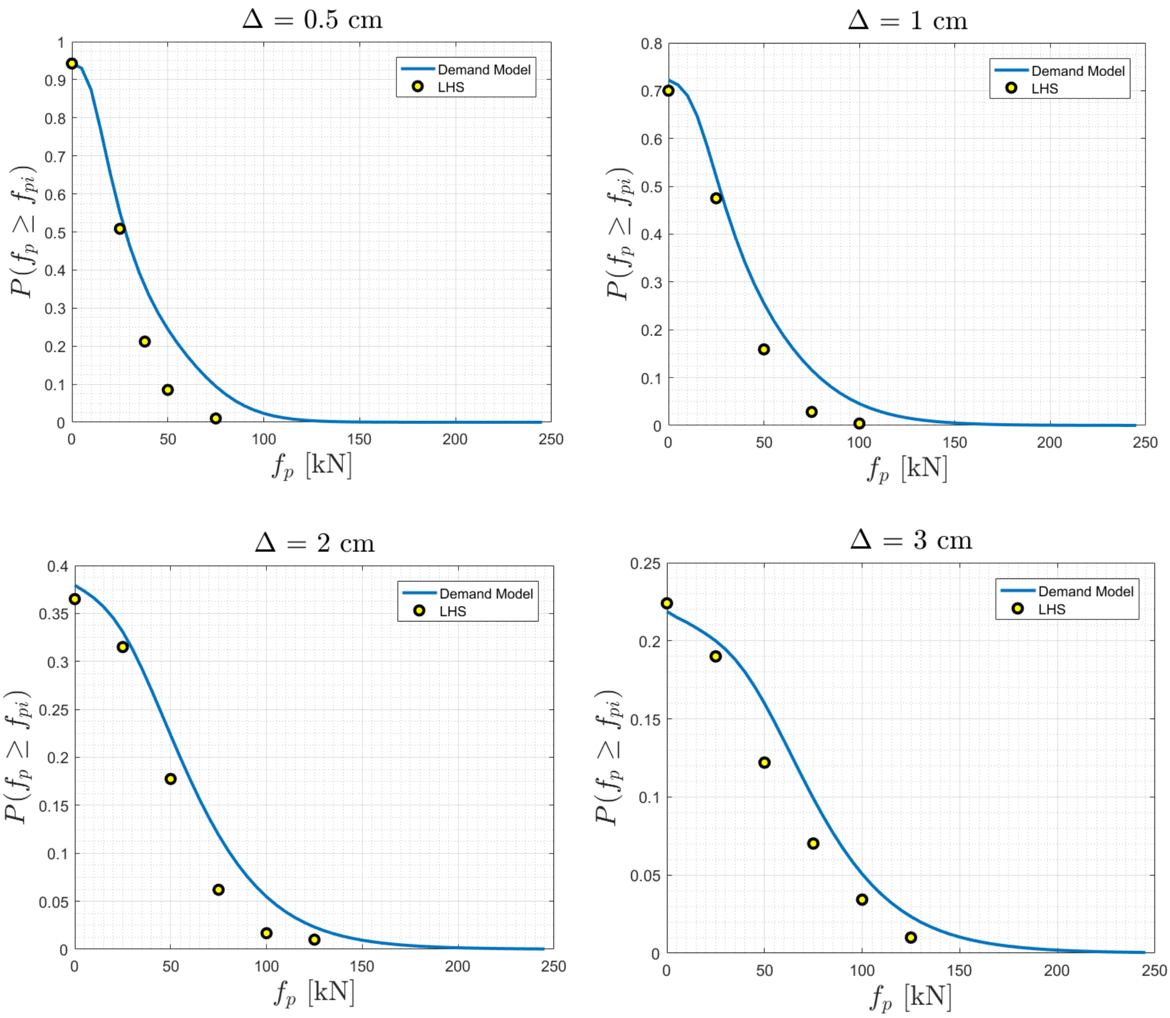


Figure 5. Comparison between the demand model and Latin Hypercube Sampling (LHS) simulation

The points provided by LHS are obtained with a minimum of 500 and a maximum of 1500 samples for a probability of order 10^{-1} and 10^{-2} respectively.
The results show a good match between the solution provided by the proposed demand model and the

reference one obtained via LHS. Although further investigations are required, the discrepancy is probably due to the lognormality assumption for the proposed probabilistic demand model and the inaccuracy of the proposed regression models.

5. CONCLUSIONS

In this study, a dimensional analysis approach has been employed for studying the pounding behavior of a single degree of freedom system and identifying the dimensionless parameters that govern the problem. An extensive parametric study has been carried out to show the influence on the impact forces of the dimensionless parameters of the model.

An analytical probabilistic demand model has been proposed based on the results of the parametric study. In particular, the adopted regression model is able to predict with high accuracy the median impact force for any combination of the input parameters, while the dispersion has a widely scattered variation which reduces the accuracy of the corresponding regression model.

The proposed model can be employed for estimating the risk of pounding force exceedance by means of the conditional intensity measure (IM) approach, assuming a lognormally distributed structural response. This has been demonstrated by comparing the mean annual frequency of exceedance of the impact forces of single pounding system obtained by the proposed approach with those obtained via random sampling. Further research will focus on improvements of the proposed regression model and on more complex pounding systems.

6. ACKNOWLEDGMENTS

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